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PREVENTION OF TURBULENT SEPARATION
BY SUCTION THROUGH A PERFORATED SURFACE

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PREVENTION OF TURBULENT SEPARATION

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TABLE OF CONTENTS

FIGURES

SYMBOLS

C_D	Total drag coefficient	$\frac{\text{Total Drag}}{q\ s}$
C_L	Airplane lift coefficient	$\frac{\text{Gross Weight}}{q\ s}$
C_p	Pressure coefficient	$1 - (\frac{U}{U_\infty})^2$
Δp	Differential pressure	
q	Dynamic pressure	$1/2\ \rho\ U^2$
S	Total wing area	
U_∞	Free stream velocity	
U	Local velocity	
u	Velocity in the boundary layer	
v_o	Local inflow velocity at the surface	
H	Boundary-layer shape parameter	$\frac{\delta^*}{\theta}$
δ^*	Boundary-layer displacement thickness	$U \int_0^h (1 - \frac{u}{U})\ dy$
θ	Boundary-layer momentum thickness	$U^2 \int_0^h [\frac{u}{U} - (\frac{u}{U})^2]\ dy$
h	A distance in the y direction greater than the boundary-layer thickness	
μ	Dynamic viscosity	
ν	Kinematic viscosity	
ρ	Density	
τ_o	Local wall shearing stress	

ABSTRACT

This paper is an investigation of the process of turbulent separation prevention by means of suction through a perforated wing. The effect of several suction distributions on the turbulent separation was studied in an effort to arrive at an optimum suction distribution. Measurements were made of the pressure distributions, boundary layer characteristics, and airplane lift and drag coefficients at various airspeeds and suction distributions.

The prevention of turbulent separation resulted in an increase in lift coefficient of 0.9 at $C_Q = 0.00316$, yielding a maximum airplane lift coefficient of 2.3 for an airplane using an unflapped 4416 airfoil section with a 5' chord. The stalling speed was 29.8 mph at a wing loading of 5.2 psf.

INTRODUCTION

For most cases, the stall of an airplane wing results from one of two causes, laminar separation at or near the leading edge or turbulent separation beginning at the trailing edge.

The stall characteristics associated with these two types of separation differ greatly. Laminar separation at the leading edge results in a relatively sudden break in the lift curve at the point where the separation occurs, while the turbulent separation, starting from the trailing edge and moving forward, causes a gradual decrease in slope of the lift curve as the stall is approached. (Figure 1 Basic Wings). Obviously then, the method of applying boundary layer control for separation prevention must depend upon the type of separation which is to be prevented. And, as would be expected, the results of the boundary layer control methods differ in their effect on the lift characteristics.

The prevention of a stall caused by laminar separation results in an extension of the lift curve to a point where the boundary layer control is no longer successful in preventing separation. (Figure 1). The prevention of turbulent separation, as employed in the present investigation, results in a change in lift curve slope even at angles well below the point where the stall occurs. (Figure 1). When one type of separation is prevented, the other type comes into prominence. For instance, an airfoil on which laminar separation is prevented will, with increasing angles of attack, stall as a result of turbulent separation starting at the trailing edge.

Separation of the turbulent boundary layer may be effectively postponed by the removal of the inner layers of relatively low momentum air flowing near the surface of a body. This removal may be readily accomplished by suction applied at the surface through a perforated skin.

With the technique of applying suction through a series of rows of small perforations, the suction distribution may be very easily tailored to fit conditions imposed on it by the pressure gradient, surface shear, etc.

The momentum equation written so as to include the influence of suction at the surface

$$v_o = (H+2)\,\theta U' + \theta' U - \frac{\tau_o}{\rho U} \qquad \text{........ (1)}$$

is a particularly useful tool for determining the amount of suction velocity which should be applied at a given point under specific conditions.

Since it is more economic of suction power to prevent the development of a large, low momentum boundary layer than to suddenly restore the momentum to a thick low energy boundary layer, it is advisable to begin controlling the momentum losses at a point on the surface which is well upstream of separation. The values required by the momentum equation are obtained at this point and a value for the rate of growth of θ with x is chosen.

In the absence of quantitative knowledge of the value of the surface shearing stress, the choice of a value for $\frac{d\theta}{dx}$ is rather arbitrary. However one may infer the relative values of τ_o from the rate of growth of the boundary layer at any position as compared to the rate of growth at some other position, provided the pressure gradients are of the same value at the two positions in question. It is obvious that the removal of almost the entire boundary layer would result in an extremely high value of surface shearing stress and would require a very large value of suction velocity to maintain the condition of constant momentum thickness. Furthermore, if in a region of high shear the rate of growth of the momentum thickness is prevented, a large suction quantity is required. For this reason, $\frac{d\theta}{dx}$ must be allowed to retain some positive value in regions of relatively high shear in order to prevent the necessity for excessive inflow velocities. However, in regions of low shear, $\frac{d\theta}{dx}$ may be reduced to zero without requiring prohibitively large inflow velocities.

Since in general the shear on an airfoil is relatively high on the forward portions and decreases to zero at separation near the trailing edge, $\frac{d\theta}{dx}$ should be allowed to retain some positive value toward the leading edge, but may be put to zero towards the trailing edge.

With a knowledge of the necessary V_o, calculated from the momentum equation, the spacing of the rows of holes is then so arranged as to give the required inflow velocities.

Small enough holes should be used so that many are required to obtain the computed inflow. The use of many rows of small holes prevents an excessive increase in shearing stress in the vicinity of each row because of the extremely thin boundary layer in these regions. For the same reason it is advisable to increase the value of V_o by increasing the number of rows of holes rather than by increasing the pressure differential across the wing surface. There are three variables concerning the inflow velocity:

1. The size of the individual holes
2. The spacing of the rows of holes
3. The pressure differential across the wing surface.

The range of hole sizes is limited on the small end by clogging difficulties and on the large end by the excessive local shear caused by very thin boundary layer. The pressure differential and the spacing of rows of given size holes depend on the inflow velocity necessary and the internal wing pressure required to prevent outflow from rows of holes located in low pressure regions of the wing. However, as has been shown, the suction required should be obtained from many rows of holes at a lower pressure differential rather than from a few rows at a great pressure differential. The experiments in the present investigation were based on the premises presented above.

TEST APPARATUS AND PROCEDURES

In general, orthodox apparatus and familiar procedures were employed in conducting the investigation.

Pressure distributions were obtained by several methods. A compact belt of ten plastic tubes (pressure tape) with perforations in each tube was arranged so that the static pressure could be measured at any desired position on the wing.

A small pitot-static device, mounted on a wand so as to enable the observer to change its position in flight, was used to measure the velocity just outside the boundary layer. The static pressure at any position could then be determined by using Bernoulli's relation on the assumption that the static pressure remained constant through the boundary layer. Static pressures were obtained by the same procedure with the outermost tube on the boundary layer "mouse." For the most part, however, the pressure tape method was used and the other methods were taken as supplementary checks.

Boundary layer characteristics were measured with a "mouse" of the usual type. It consisted of ten total head tubes in a one-inch height and one static pressure tube. The pressures were led to a water-filled, multiple U-tube manometer where they were photographically recorded. The photographs were then enlarged and the data were reduced in the usual manner.

The relative angles of attack in flight were determined with a yaw-head type angle-of-attack device mounted on a boom which held it well away from the influence of the wing and above the aerodynamic center.

The total airplane drag coefficients were determined from the sinking speed measured at various flight speeds. From these measurements the L/D values at each airspeed were determined; from this data, knowing the lift coefficient at each airspeed, the total drag coefficient was obtained for each airspeed considered.

As some indication of the surface shear was necessary to the computations of the inflow velocities required, the following technique was employed. A solution was made from naphthalene flakes and petroleum ether and this solution was sprayed in a thin film on the surface of the wing and covered with a paper sheath which was removable in flight. When the test conditions had been established, the paper sheath was removed and the film of naphthalene exposed to the air. Since the rate of sublimation of the naphthalene was an indication of the shear, the naphthalene in the high shear regions disappeared first. By observing the progress of the evaporation of this film, some indication of the shear distribution could be inferred.

A variation of an integrating wake rake was also used to measure the boundary layer thickness. (Figure 2). This instrument was so constructed that the integrated total pressure across the boundary layer was measured. (Reference 1). The integrated pressure was opposed to the free stream total pressure and the Δ p measured. This pressure differential may be interpreted in the following manner.

Since $H_o = H_{\ell}$; where H is Bernoulli's constant and h is the height of of the instrument.

$$\Delta p = H_{\ell} - \frac{1}{h}\int_o^h H\,dy$$

$$= q_{\ell} - \frac{1}{h}\int_o^h q\,dy$$

Assuming p constant through the boundary layer.

$$\Delta p = \frac{\rho}{2h}\int_0^h (U^2 - u^2)\, dy = \frac{\rho}{2h}\int_0^h (U + u)\,(U - u)\, dy$$

$$= \frac{\rho}{2h}\int_0^h (U^2 - Uu)\, dy + \frac{\rho}{2h}\int_0^h (uU - u^2)$$

$$= \frac{\rho U^2}{2h}\int_0^h (1 - \frac{u}{U})\, dy + \frac{\rho U^2}{2h}\int_0^h (\frac{u}{U} - \frac{u^2}{U^2})\, dy$$

$$= \frac{\rho U^2}{2h}(\delta^* + \theta)$$

$$\Delta p = \frac{\rho U^2 \theta}{2h}(H + 1)$$

or assuming H for the turbulent boundary layer ≈ 1.4.

$$\theta \approx \frac{\Delta ph}{1.2 \rho U^2}$$

The values of θ obtained by this method were used only relatively, not as absolute values. This method of measuring θ was used mainly to determine the optimum Δ p across the skin. The rake was mounted at some position on the wing and the internal pressure was varied until a minimum reading was obtained.

The perforation of the wing panels was accomplished in two ways. In the fabric sections, the holes, which were 0.018" in diameter, were punched with a machine fabricated from a household "Mix-master." This machine ran on a long straight track and automatically punched twenty holes per inch using a No. 10 sewing needle, which measures 0.018" in diameter. The holes in the plywood-covered leading edge were made by using light hand drills with #77 twist drills. The plywood leading edge had previously been covered with fiberglass cloth, which was doped in place, to make up for the loss in strength incurred by the drilling of the holes.

The porosity of the perforated sections was calibrated by using test samples in the laboratory and by tests conducted on the wing panels themselves. The flow through the holes was determined as a dimensional coefficient in cu. ft./ sec. - ft. of holes - $\#/f^2$. Thus, by knowing the static pressure gradient, the internal wing pressure, and the disposition of the rows of holes on the wing, the flow quantity at any air-speed could be computed.

TESTS

All tests were made on a modified Schweizer TG-3A sailplane with a wing area of 237 f^2 AR = 12.3 of a wing loading of 5.2 $\#/f^2$ (Figure 3). The maximum lift coefficient obtainable under the above conditions was 1.38, which occurred at an airspeed of 38.5 mph. The stall began as a turbulent separation at the trailing edge and moved forward with increasing angle of attack. The areas to which suction was applied and the results of the various distributions tested are shown in Figure 4.

The first suction distribution investigated consisted of 50 spanwise rows of 0.018" diameter holes, spaced 20 per inch in each row. The rows of holes, which ran the full span of the wing, were punched with the first row at the 35% chord station and with subsequent rows back to the trailing edge.

The chord-wise spacing of the rows was calculated from the inflow velocity distribution necessary to keep the momentum thickness of the boundary layer constant in the pressure gradient existing on the wing at 40 mph. The initial momentum thickness was to be that of the uncontrolled boundary layer on the forward part of the wing when it had reached the 35% station.

The separation on this section was delayed sufficiently to allow the airplane to slow down to an airspeed of 35.5 mph, at which speed it was operating at a lift coefficient of 1.61. The C_Q necessary to achieve this condition was 0.00149.

Boundary layer measurements taken at this speed revealed that the boundary layer momentum thickness at the 35% chord station had increased sufficiently, because of the lower velocities and larger pressure gradients, to render the suction distribution incapable of controlling the momentum losses in the boundary layer.

The second suction distribution investigated consisted of the porosity considered above plus the additional porosity added ahead of the 30% chord station. Since the momentum thickness at the 30% station had increased to a value larger than that necessary to meet the conditions required to make the rear perforated section effective in reducing momentum losses, it seemed advisable to reduce the momentum thickness at the 30% station rather than to alter the porosity on the aft section. This reduction of the momentum thickness was to be accomplished by means of suction applied through rows of holes drilled in the plywood leading edge of the airfoil. The spacing of the rows was determined in the manner described using the pressure gradient, momentum thickness, and measured flow coefficient. The rows were drilled 10 holes to the inch in the leading edge from the root of the beginning of the tapered section. This additional suction reduced the stall speed of the airplane to 32 mph, a lift coefficient of 1.98. The value of suction coefficient, C_Q, at this condition was 0.00264.

The momentum thickness at 35%, although reduced considerably below that of the impervious wing, was still not down to the value necessary to meet the requirements originally set down for the porous area at the rear of the wing. No amount of suction applied at the leading edge was successful in thinning the entering boundary layer thickness to the required value. (The nature of this phenomenon will be discussed in more detail later.) Rather than alter the porosity on the leading edge, it was decided, because of ease of operation, to adjust the rear section to meet the new conditions to which it was to be subjected.

Therefore in the third distribution additional rows of holes were punched in the rear portion of the airfoil and the rows of holes on the leading edge were extended to the tips. An additional 14 rows of holes were punched between the rows of holes already in this section beginning at the 35% chord station. At the end of these 14 additional rows, 7 rows were spaced alternately between rows existing in this region. These extra holes raised the C_Q to 0.00316 and increased the lift coefficient to 2.2, at an airspeed of 30.2 mph. The inability of the wing to remain unstalled at greater angles of attack was again attributed to the momentum thickness at 35% reaching a value too large to allow the rear porous area to be effective in controlling the momentum losses.

In the fourth distribution, the porosity on the leading edge was systematically altered and the effects of this alteration on the momentum thickness at the 30% chord station were studied. (The details of this study are to be presented later.) The results of the investigation indicated that the holes in the area between the 1.5% and the 5% chord station should be closed. This alteration allowed the airplane to slow down to a speed of 29.8 mph, an airplane lift coefficient of 2.28 at a value of $C_Q = 0.00316$. The lift curve and drag polar for this condition are shown in Figures 9 and 10.

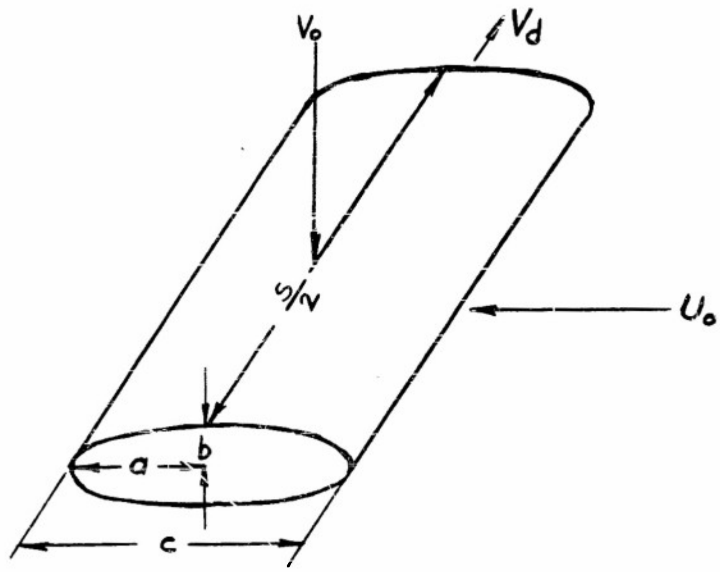
DISCUSSION

As a comparison, the results of the present investigation are shown with the results of other methods used for lift augmentation by suction. The various systems considered are shown schematically in Figure 7, References 2-7. So that a more accurate comparison might be drawn, an effort was made in the selection of the examples to choose cases in which auxiliary devices such as flaps, slats, etc. were not employed. The comparison was made on the basis of the minimum suction required for the highest lift coefficient attained in each case. (Figure 6). As a measure of the effectiveness of the suction used, the quantity $\frac{\Delta C_L}{C_Q}$ is presented. In all cases except IV, the values of lift coefficients quoted were section lift coefficients. In case IV the lift coefficients referred to are airplane lift coefficients.

Case I shows a considerable increase in maximum lift coefficient at, however, a rather extravagant suction quantity. The low value of $\frac{\Delta C_L}{C_Q}$ possibly indicates that the suction available was not employed in the most economic fashion. Also, in case II, where the suction quantity is lower, there is an accompanying decrease in the lift increment which results in a low amplification factor, indicating improper disposition of suction available.

Case III is perhaps out of place in this comparison in that, aside from the fact that it involves the use of a flap, it is obviously not strictly a boundary-layer control system but is rather a circulation producing device. It is of interest nevertheless for several reasons. It illustrates that extremely high lift coefficients may be obtained by the use of suction applied at the surface of an airfoil. However, it may also be used to show the penalties which are involved in the use of the extremely large suction quantities inherent in this system.

The following computations show the ducting velocities which would be associated with this type system. In the calculation, the entire interior wing cross-section is assumed to be available for ducting.



a, b = major and minor axes of ellipse

c - chord of wing

e - eccentricity of ellipse

$\frac{S}{2}$ - semi-span of wing

C_Q - $\frac{V_o}{U_o}$; flow coefficient

U_o - free stream velocity

V_o - average inflow velocity

V_d - velocity at exit of wing panel

Area of ellipse = πab

Area of wing panel = $\frac{Sc}{2}$

Quantity flow into wing = Q = $\rho A_w V_o$ = $S\, a\, V_o$

$$V_d = \frac{Q}{\rho \pi ab} = \frac{\rho S a V_o}{\rho \pi ab}$$

$$= \frac{S V_o}{\pi b} = \frac{S V_o}{\pi (ea)} = \frac{2\, S V_o}{\pi e\, 2a}$$

$$= \frac{2}{\pi e} \frac{S}{c} V_o = 0.637\ AR\ C_Q\ V_o, \text{ where } AR = \text{aspect ratio}$$

or, for the case under consideration, where e = 0.35, C_Q = 0.11

$$V_d = 2\ AR\ U_o$$

assuming AR = 6, U_o = 50 ft. per second

V_d = 600 ft. per second = velocity of flow from each wing panel.

For these conditions and a lift coefficient = 7.3, the wing loading would be 46.7 #/f^2, which is within the range of present day wing loadings.

From the foregoing, it may be seen that it would be at least desirable, if not mandatory from a practical point of view, to have more reasonable velocities inside the wing. In order to reduce the high velocities due to suction, the lift increment must be obtained with lower values of C_Q.

Case V is a good example of the attainment of a sizeable lift increment at low values of C_Q. In this case, the stall resulted from a sudden laminar separation near the leading edge behind which the flow never reattached. The application of a small amount of suction in the vicinity of the laminar separation point prevented the laminar separation. And, according to the concluding remarks in the report, the subsequent stall with suction appeared to result from turbulent separation moving forward from the trailing edge.

In case VI the same situation prevailed as in V, a laminar separation at the leading edge being responsible for the stall. However, in this case the investigators chose to defer the laminar separation by means of a slot located near the leading edge. The lift increment obtained was of the same order as in case V but at a higher value of C_Q. It was reported that the stall with only the nose slot operating resulted from turbulent separation from the trailing edge. For further increases in lift, the mid-chord slot was activated with the intention of delaying this turbulent separation at the trailing edge. As indicated in Figure 6 (VII) an additional increment was obtained, but the additional C_Q necessary was disproportionately large resulting in a lower value of $\frac{\Delta C_L}{C_Q}$ for both slots than that for the nose slot alone. If the effectiveness of the rear slot had been equal to that of the nose slot, the lift increment gained by the rear slot should have required no more C_Q than that required by the nose slot. This, then, would indicate that the suction applied at the rear slot might better have been employed in some other fashion.

Case IV shows a good lift increment at a low value of C_Q resulting in a high $\frac{\Delta C_L}{C_Q}$ and demonstrating an economic utilization of the suction.

This comparison should at least show that, of the various methods employed in applying suction to an airfoil, some methods are more effective in the attainment of additional lift increments than others.

As mentioned in the description of the tests performed on the perforated wing, experiments indicated that the rows of holes between 1.5% and 5% should be sealed. In the course of conducting boundary layer surveys on the leading edge of the airfoil in the impervious condition, the presence of a so-called "laminar bubble" was detected at approximately the 4% chord station. It was expected at the time that, when the leading edge was drilled to reduce the momentum losses, the suction applied would eliminate the localized laminar separation. However, when the forward areas were perforated, subsequent boundary layer surveys showed that instead of the bubble disappearing under suction it actually increased both in height and in chordwise length. Figure 7 shows the influence of the suction on the localized laminar separation. The effect of this bubble on the boundary layer thickness downstream was of prime concern since the suction was applied with the notion of thinning the boundary layer. Therefore, a series of tests was run wherein the suction in the vicinity was altered by means of closing rows of holes instead of altering the pressure differential. Figure 8 shows the results of this experiment. Since the momentum thickness at the 35% station reached a minimum with the rows of holes beginning at the 5% chord station, the rows were sealed back to this point for subsequent experiments. Although this phenomenon is not fully explained, it seems to follow the conclusion reached in Reference 7 which states that the beginning of the application of suction should be just downstream of the separation point of the impervious section. However, in order to devote more attention to the basic problem of turbulent separation detailed investigation of this phenomenon was deferred.

Attention should also be directed to Figure 1 which shows the effect on the lift characteristics of leading edge and trailing edge suction. While the leading edge suction extends the lift curve at its same slope, the trailing edge suction changes the slope of the lift curve. These changes occur, however, only when the leading edge suction is preventing separation at the nose of the airfoil and the trailing edge suction is preventing separation from the trailing edge. In general, the effect of suction on the lift characteristics of an airfoil depends on the thickness of the airfoil and the manner in which the suction is employed; prevention of laminar separation extends the lift curve and application of distributed suction on the rear portion of the airfoil changes the slope of the lift curve.

CONCLUDING REMARKS

From the results of this investigation and the comparison with other methods, the following conclusions are drawn:

1. Separation prevention of the turbulent boundary layer accomplished by distributed suction through perforations is an effective and economical method of lift augmentation.
2. The prevention of turbulent separation by means of distributed suction may increase the slope of the lift curve resulting in a higher lift coefficient at a given angle of attack.
3. In general, it is more economic of suction quantity to prevent turbulent separation by means of distributed suction than by concentrated suction as in the case of a slot.

The lift increment obtained in this investigation was limited by the capacity of the blowers used to evacuate the rear portions of the wing. The capacity of the blower was such that the punching of more holes in the rear portion of the wing would have resulted in outflow from holes in the lower pressure regions of the wing since the entire rear section of the wing was one compartment. Some of the difficulties encountered on the leading edge were attributed to the fact that the fiberglass covering considerably roughened the surface. Further investigations with smoothed leading edge are in progress.

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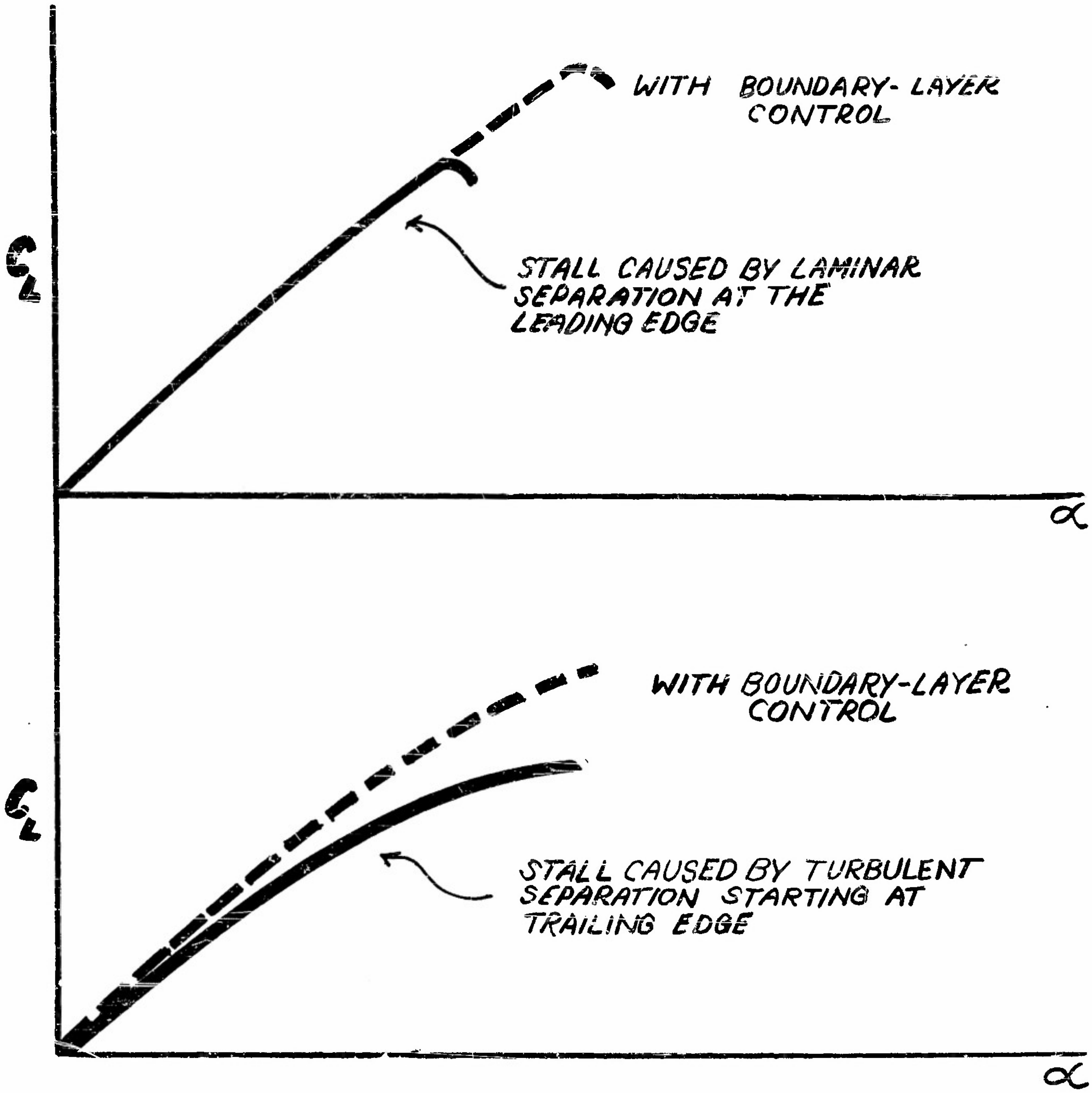
FIGURE 1



EFFECT OF SEPARATION PREVENTION ON LIFT CURVE FOR TWO TYPES OF STALLS

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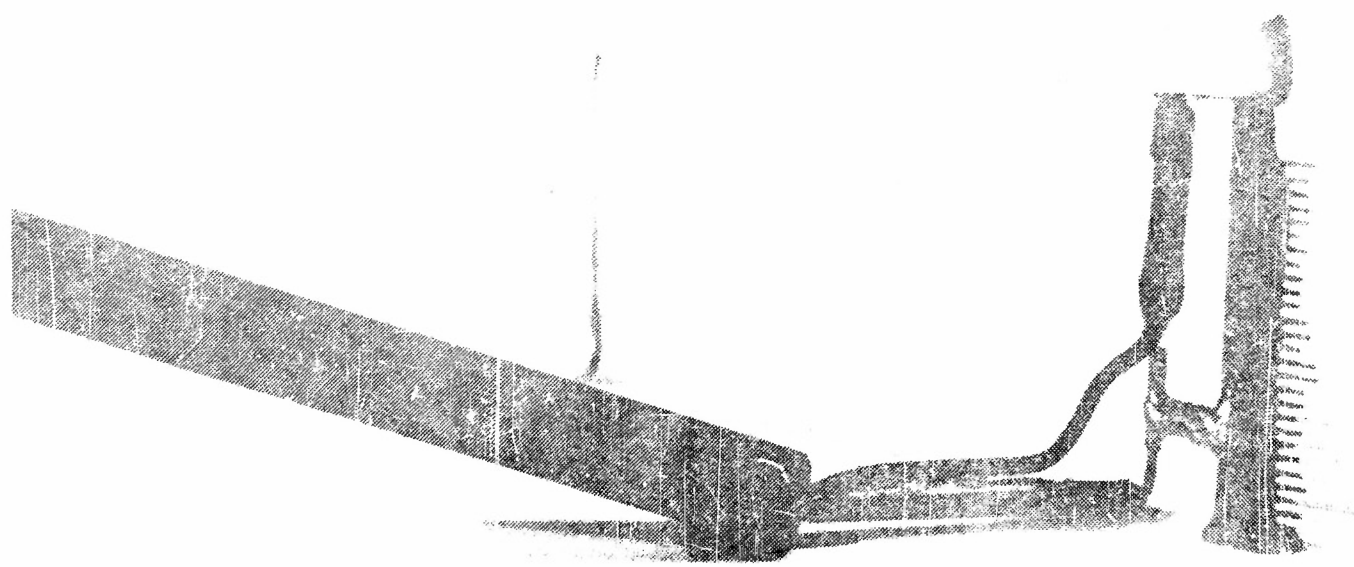
FIGURE 2



INTEGRATING BOUNDARY LAYER MOUSE

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FIGURE 3

MODIFIED SCHWEIZER TG - 3A SAILPLANE

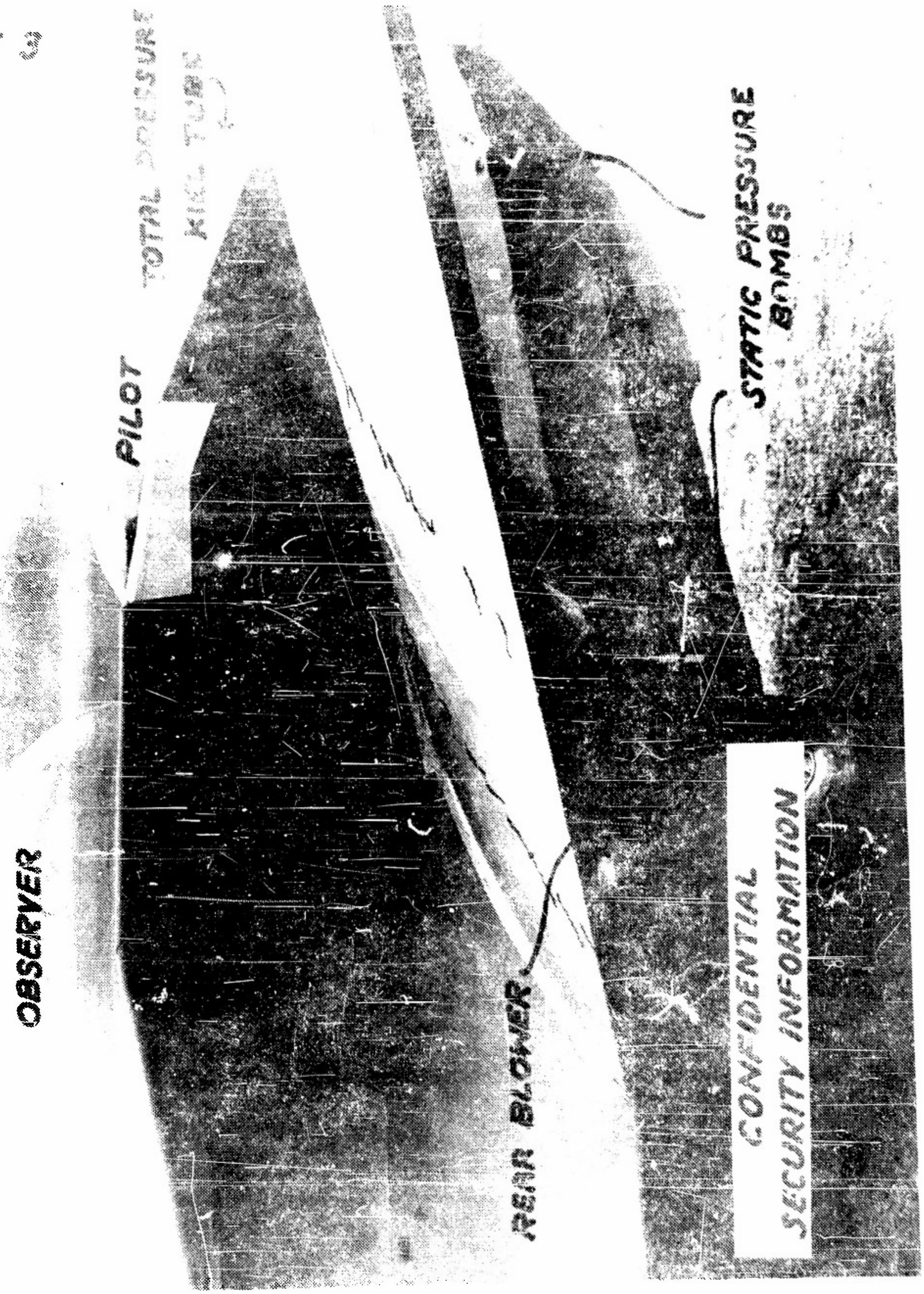

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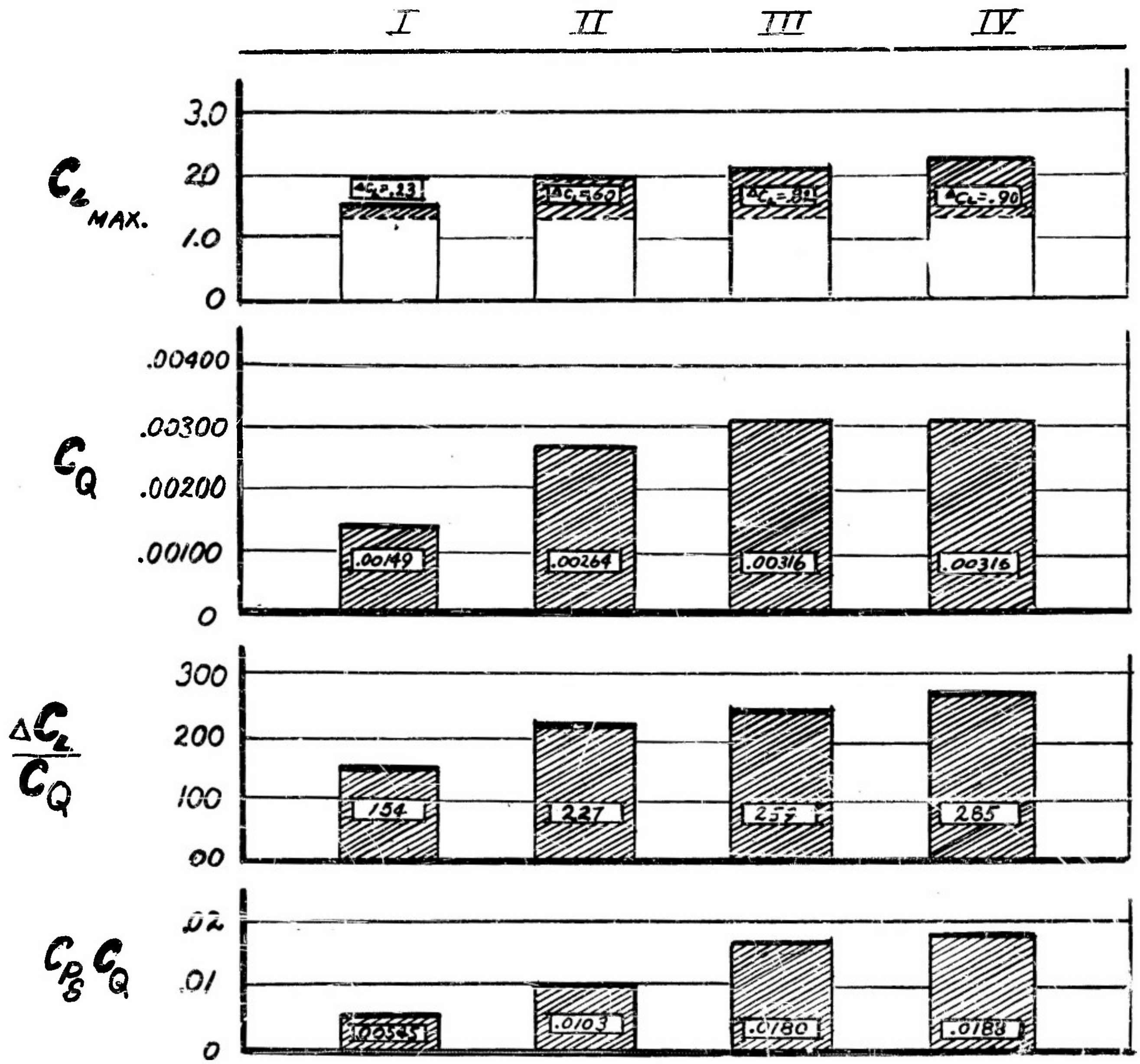
FIGURE 4-A



RESULTS OF POROUS AREAS TESTED

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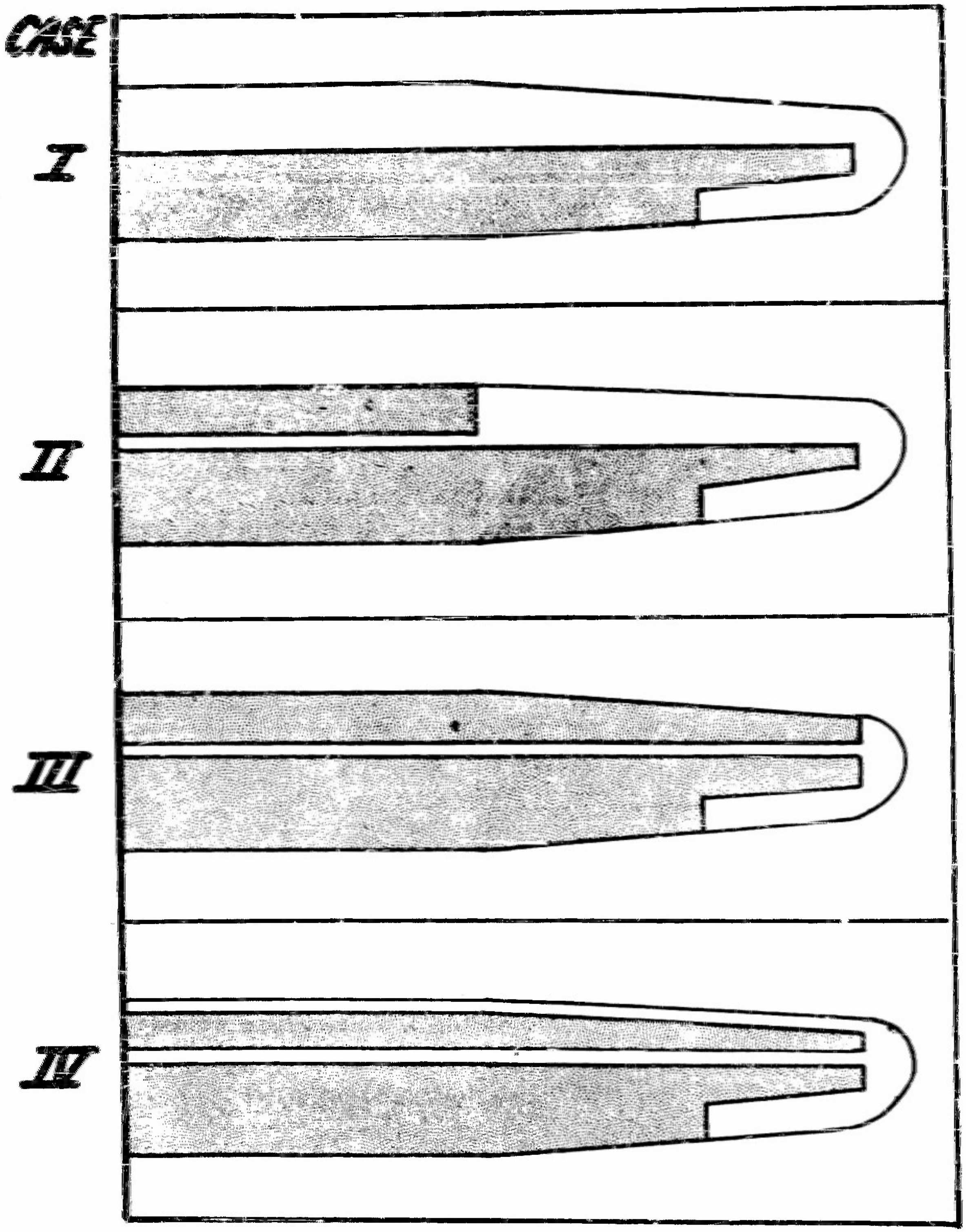
FIGURE 4



SCHEMATIC OF POROUS AREAS

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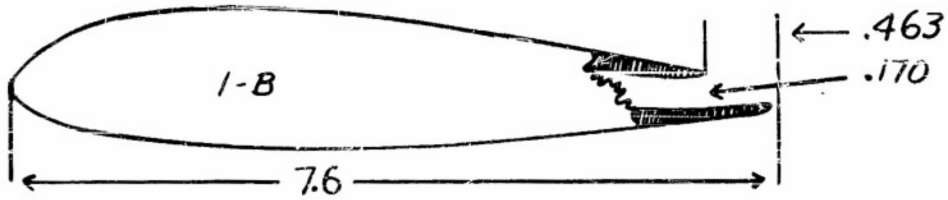
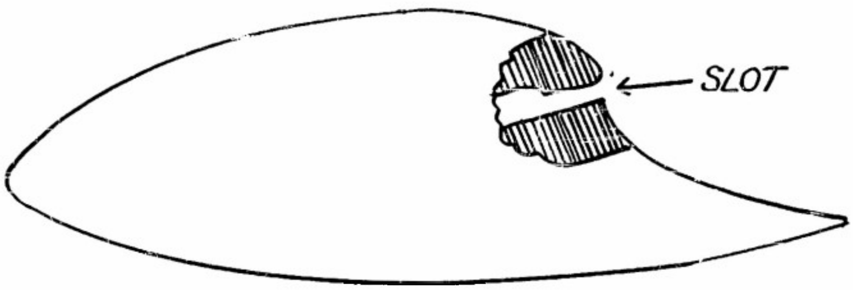
FIGURE 5



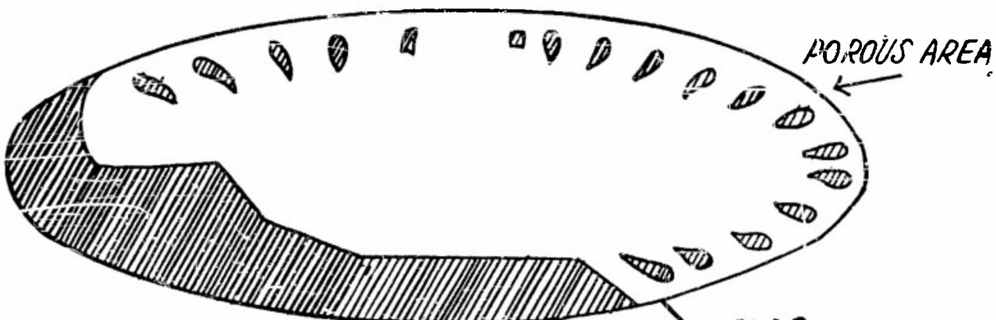
I

PRINCETON T.E. SLOT MODEL 1-B



II

BRITISH 31.5% THICK SLOTTED AIRFOIL



III

AERO-JET 35% THICK ELLIPSE AND FLAP

SCHEMATIC DIAGRAMS OF VARIOUS HIGH-LIFT SUCTION SYSTEMS

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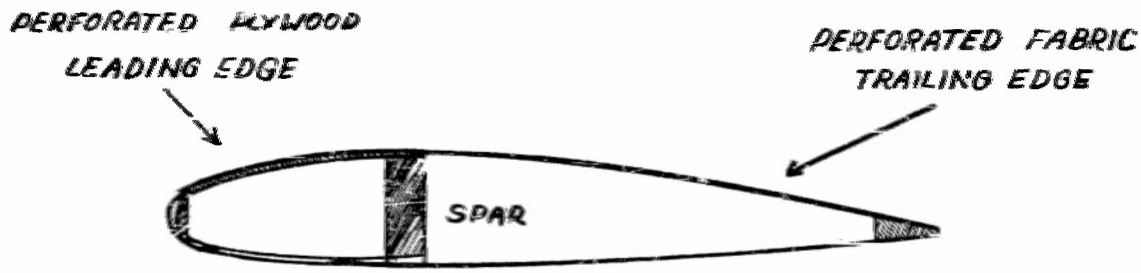
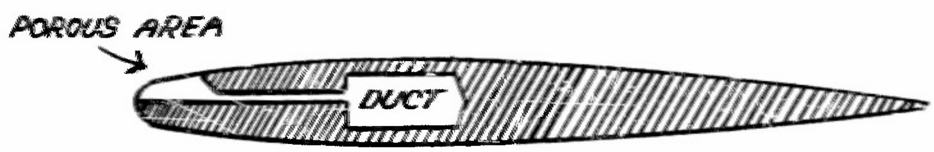
FIGURE 5 (CONTINUED)



IV

NACA 4416 AIRFOIL WITH PERFORATIONS AS USED AT MISSISSIPPI STATE COLLEGE



V

NACA 10.5% THICK AIRFOIL WITH POROUS LEADING EDGE

VI & VII

NACA 63-012 AIRFOIL WITH LEADING EDGE AND MID-CHORD SUCTION SLOTS

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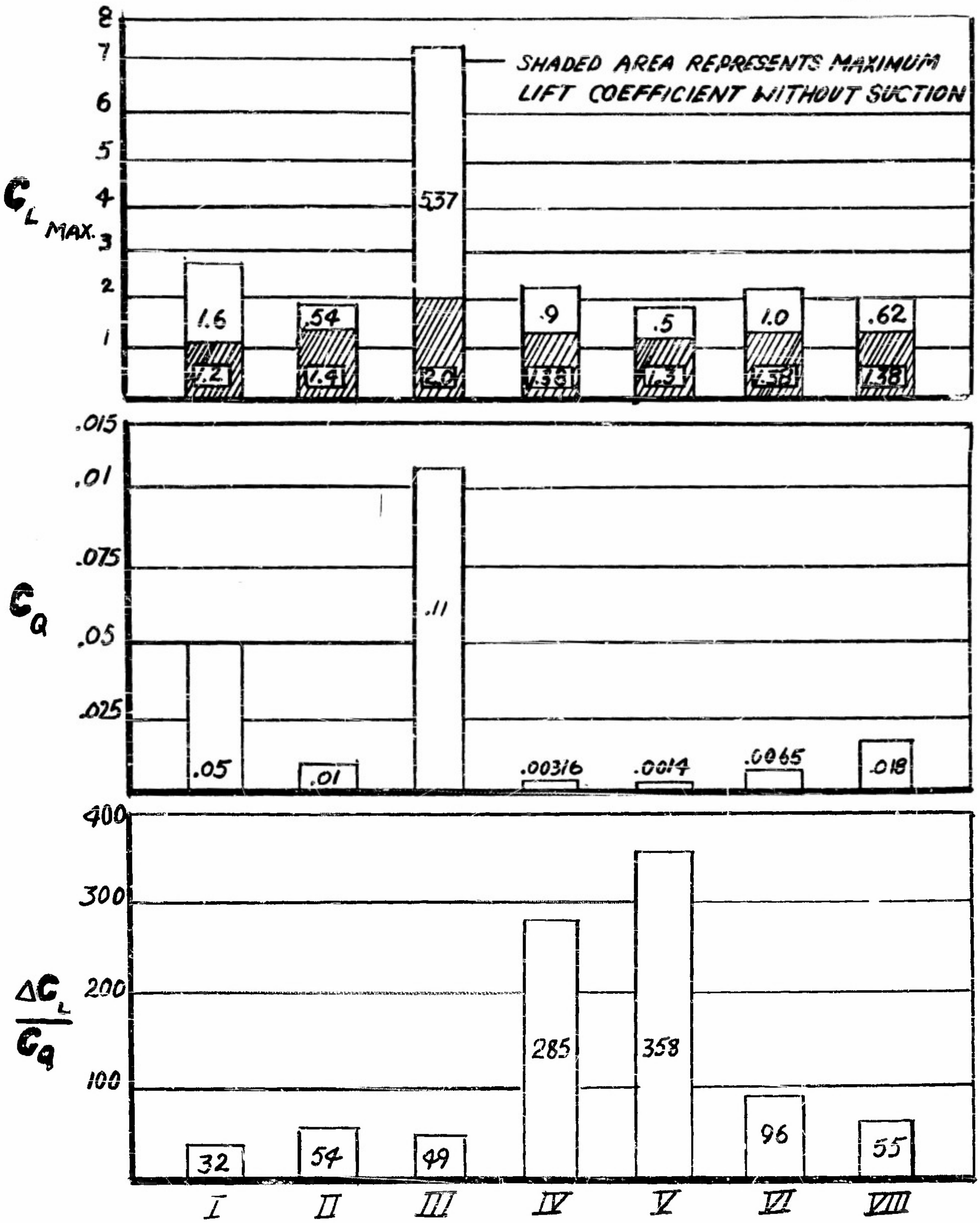
FIGURE 6



COMPARISON OF HIGH-LIFT SYSTEMS

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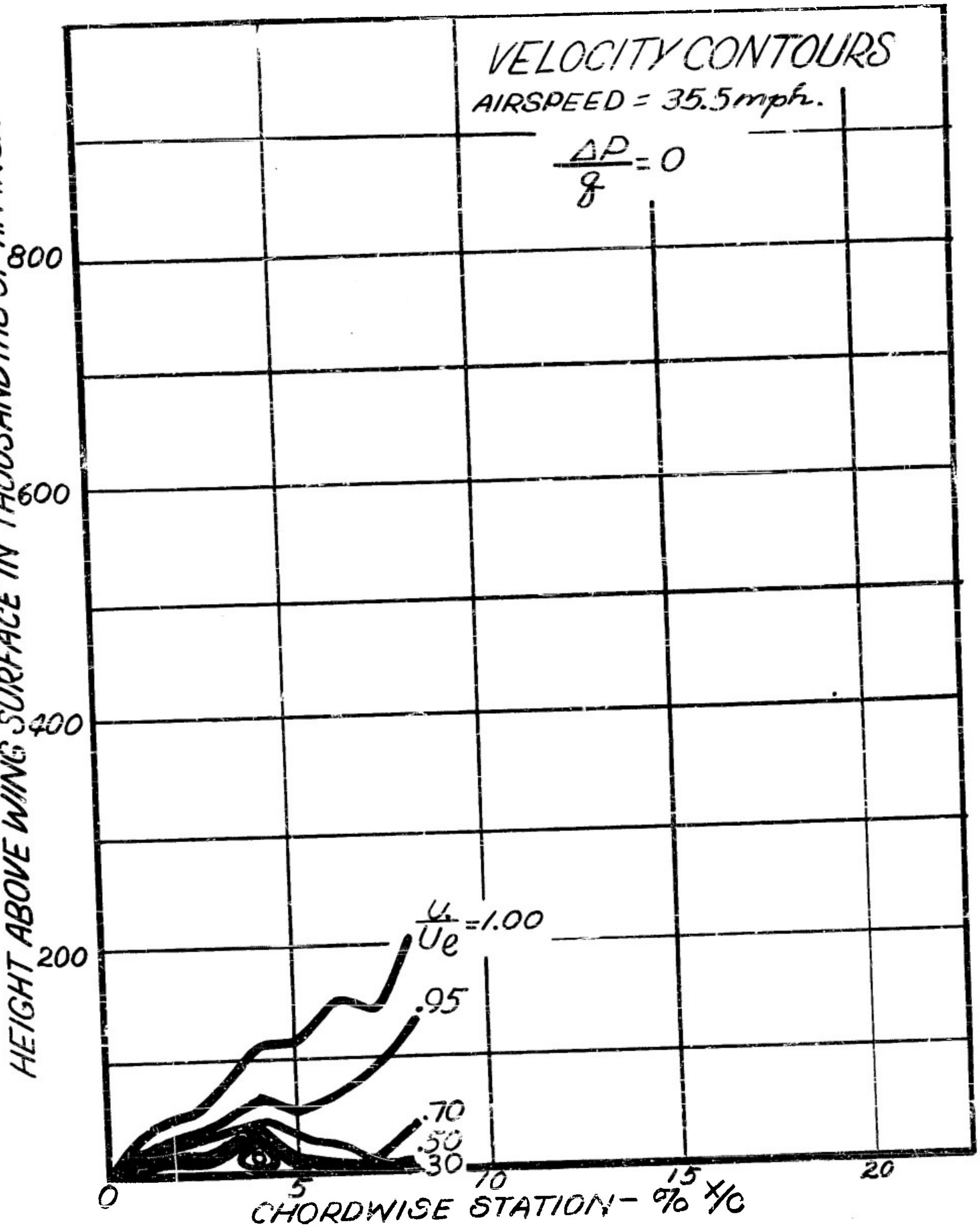
FIGURE 7



SUCTION EFFECT ON A REGION OF LOCALIZED LAMINAR SEPARATION

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FIGURE 7(CONTINUED)

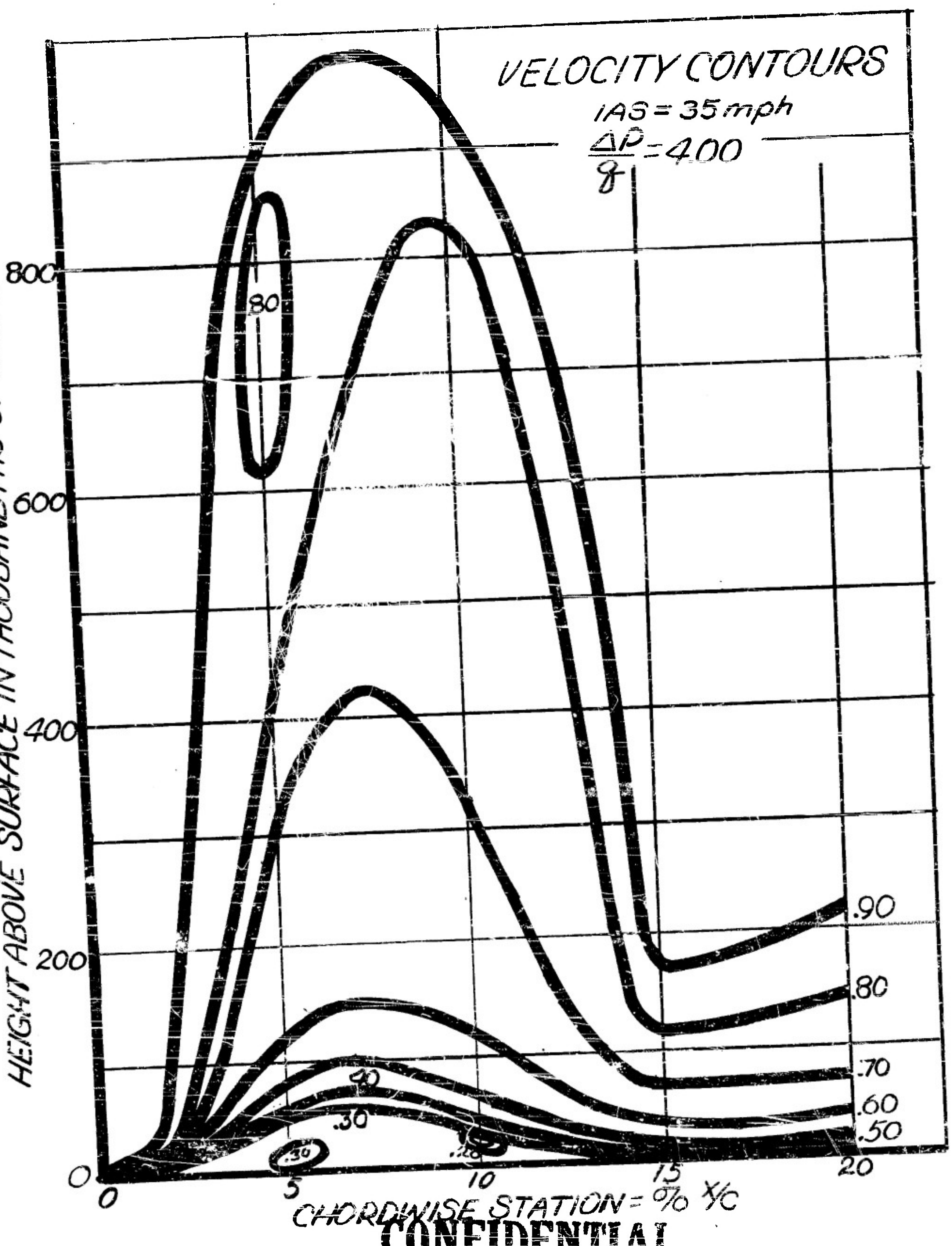

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FIGURE 7 (CONTINUED)

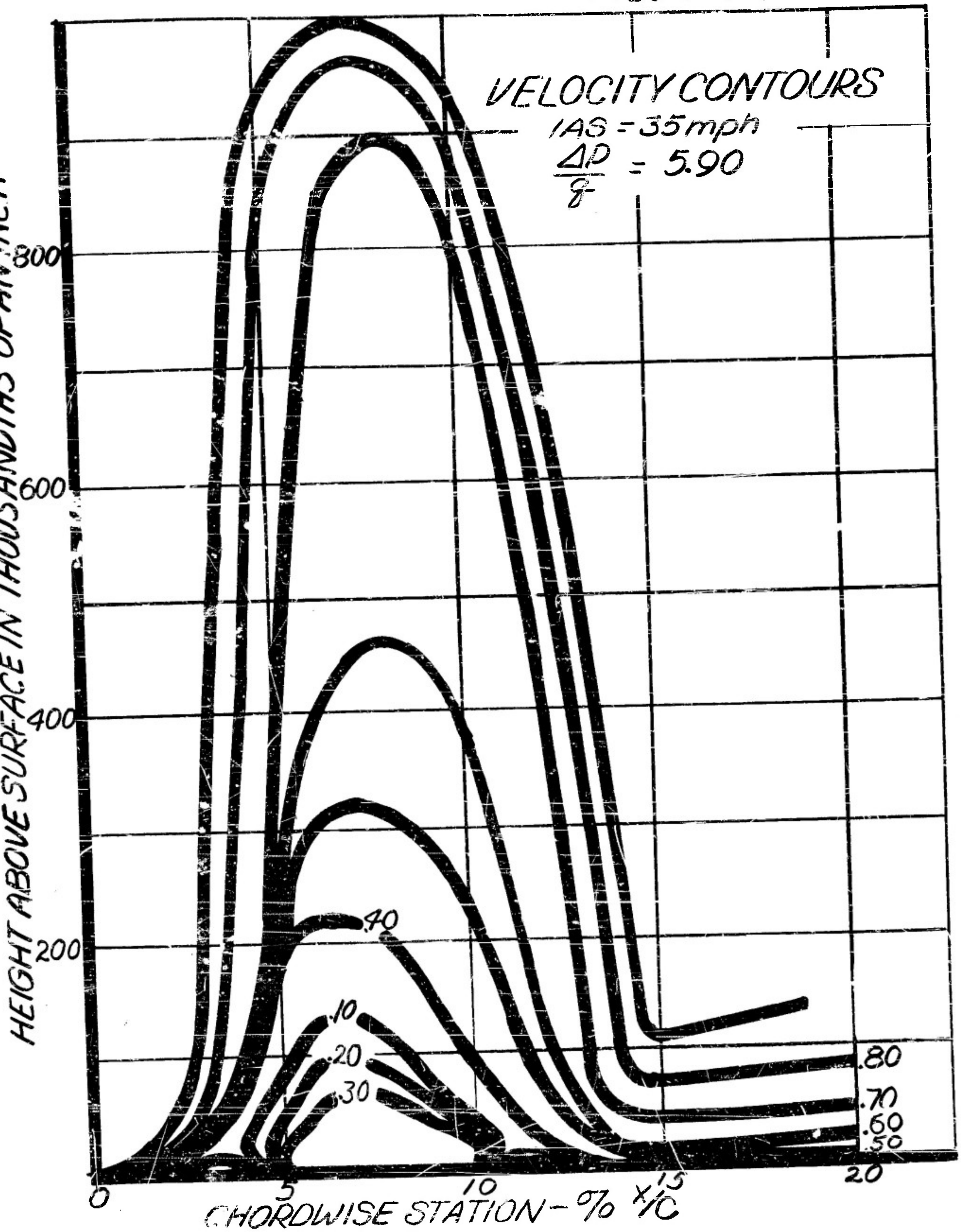

FIGURE 8

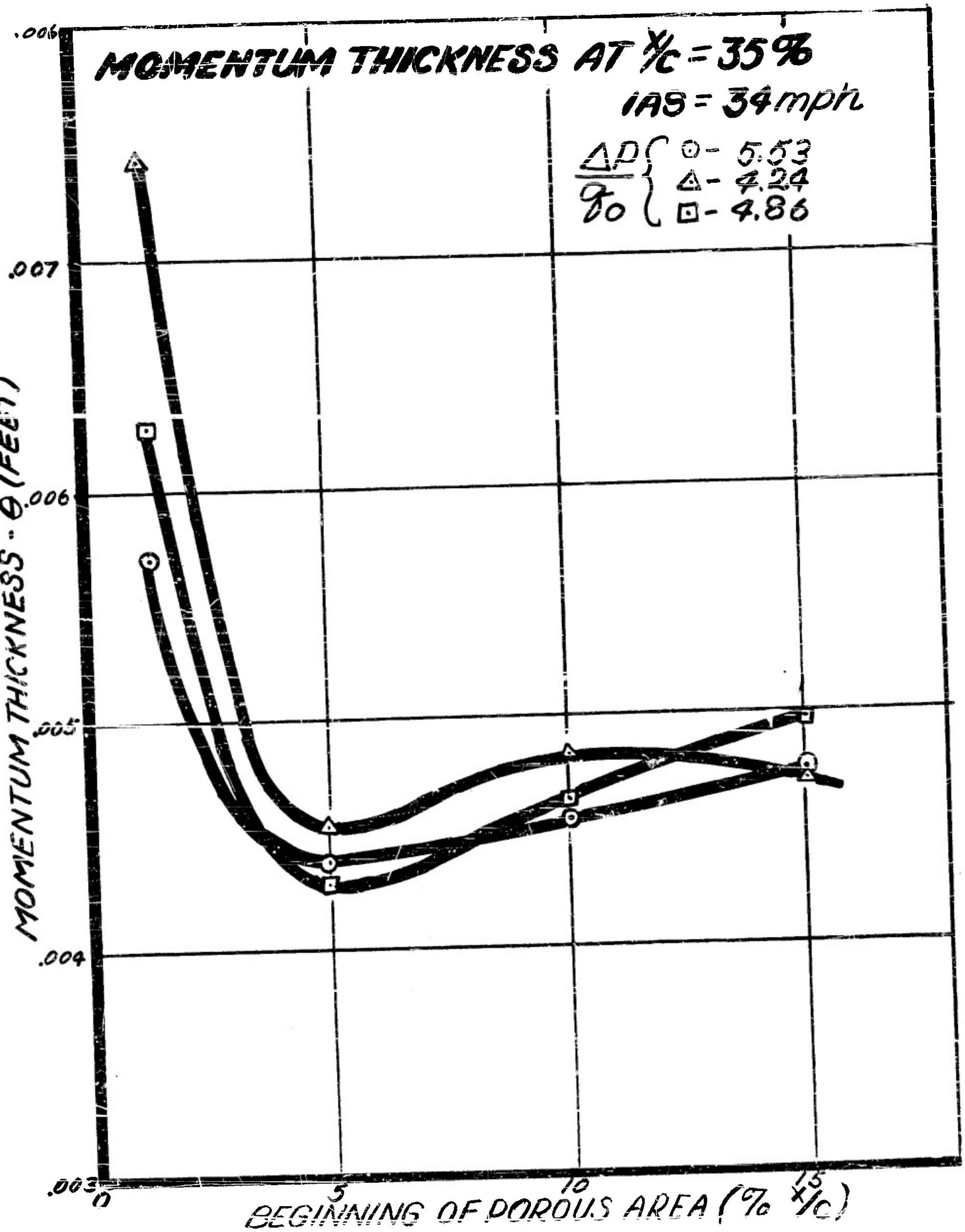
MOMENTUM THICKNESS AT X/C = 35%
IAS = 34 mph
ΔP/q0
⊙ - 5.53
△ - 4.24
□ - 4.86
MOMENTUM THICKNESS - θ (FEET)
.008
.007
.006
.005
.004
.003
0
5
10
15
BEGINNING OF POROUS AREA (% X/C)

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FIGURE 9

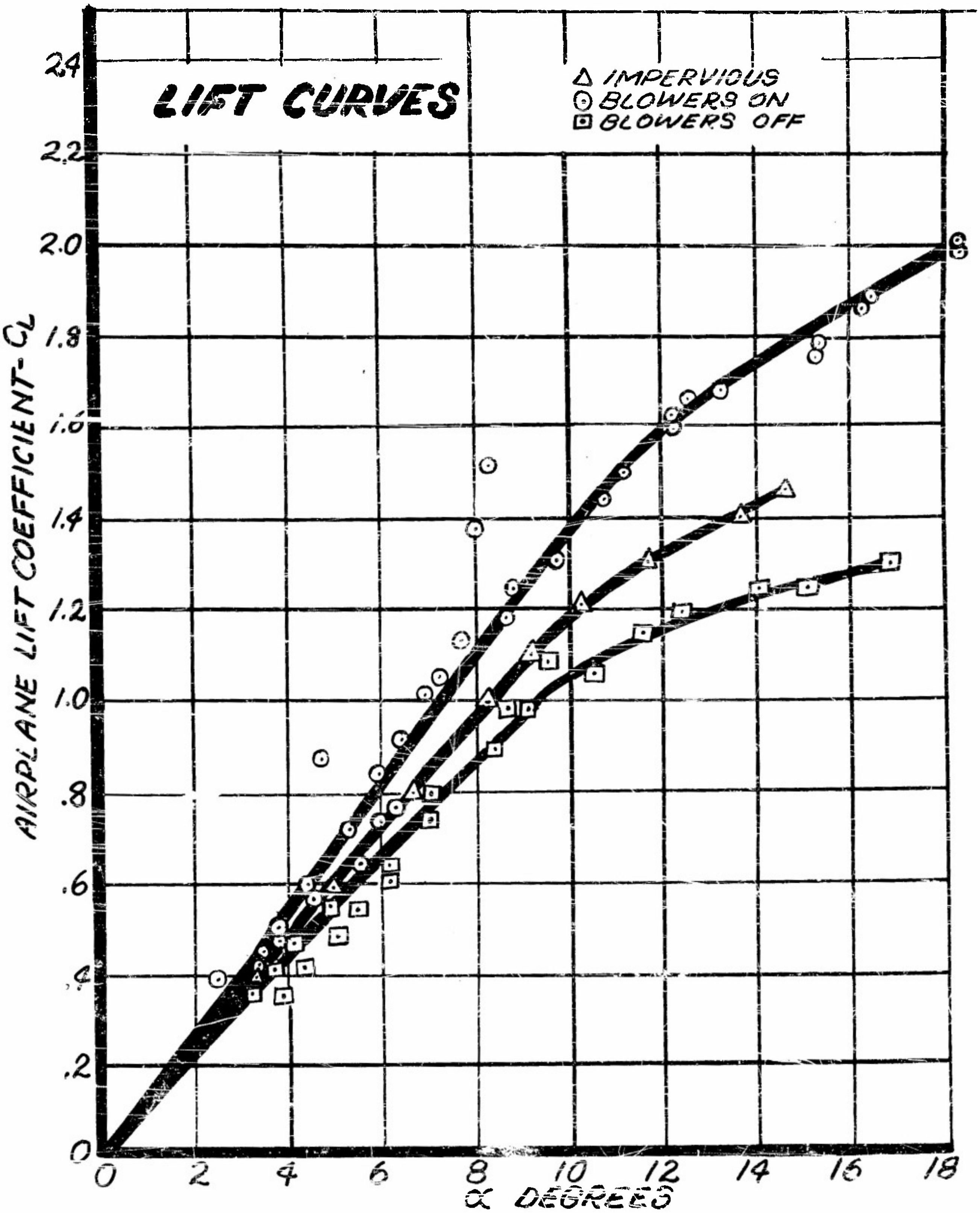

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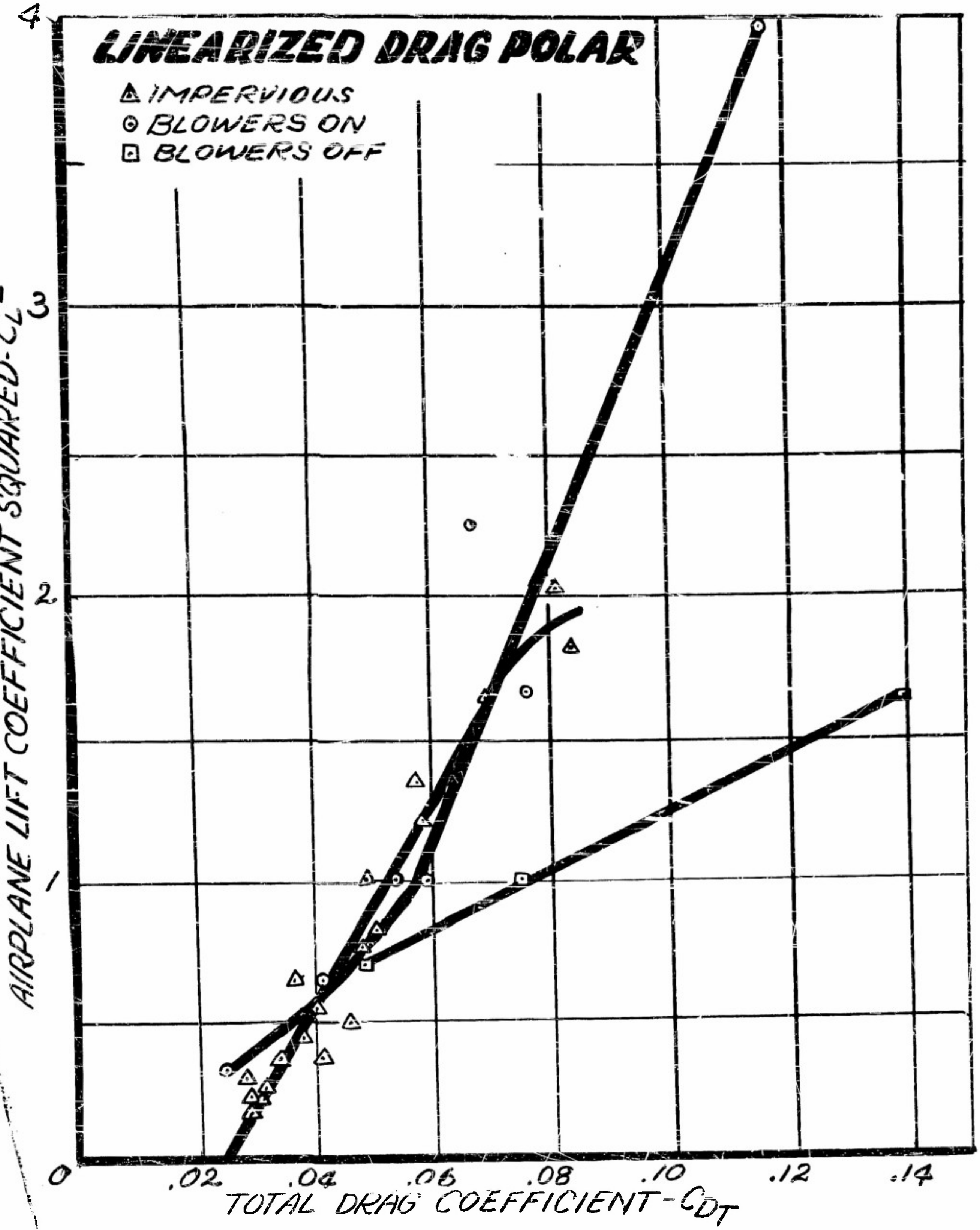
FIGURE 10


LINEARIZED DRAG POLAR
IMPERVIOUS
BLOWERS ON
BLOWERS OFF
AIRPLANE LIFT COEFFICIENT SQUARED - C_L^2
4
3
2
1
0
.02
.04
.06
.08
.10
.12
.14
TOTAL DRAG COEFFICIENT - C_{D_T}